# SIMULATION OF WATER DISTRIBUTION SYSTEMS

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## ABSTRACT

In this paper a software package offering a means of simulating complex water distribution systems is described. It has been developed in the course of our investigations into the applicability of neural networks and fuzzy systems for the implementation of decision support systems in operational control of industrial processes with case-studies taken from the water industry.

Examples of how the simulation package have been used in a design and testing of the algorithms for state estimation, confidence limit analysis and fault detection are presented. Arguments for using a suitable graphical visualization techniques in solving problems like meter placement or leakage diagnosis are also given and supported by a set of examples.

## INTRODUCTION

The optimal control of water systems is a challenging problem because the models are non-linear and large-scale and measurements are noisy and frequently incomplete.

This nonlinearity and large-scale quite often makes the behaviour of a water distribution system unpredictable and hugely dependable on a specific operating condition and the fact that some measurements can be missing or very inaccurate can add another level of difficulty for an engineer or researcher attempting to devise robust methods for monitoring and/or control of such a system.

While for the well maintained water distribution systems the normal operating state data can be found in abundance the instances of abnormal events are not that readily available. In order to observe the effects of abnormal events in the physical system one sometimes is forced to resort to deliberate closing of valves to simulate blocked pipes or opening of hydrants to simulate leakages (Carpentier and Cohen 1993). Although such experiments can be very useful to confirm the agreement between the behaviour of the physical system and the mathematical model, it is not feasible to carry out such experiments for all pipes and valves in the system during the whole day or days as might be required to thoroughly test novel approaches or obtain enough data to design new algorithms.

It is an accepted practice that, for processes where the physical interference is not recommended or even dangerous, mathematical models and computer simulations are used to predict the consequences of some emergencies.

This paper gives an account of the software package and extensive computer simulations which helped enormously in developing and demonstrating different properties of the algorithms for state estimation, confidence limit analysis, pattern recognition, fault detection and decision support.

Ability to simulate measurement errors and noise, and in particular gross measurement errors for different configurations and types of meters resulted in identification of strengths and weaknesses of different state estimation procedures (Gabrys and Bargiela 1995). The ease with which a configuration of meters can be changed in the simulator has also benefited studies concerning the measurement uncertainty impact on the accuracy to which state estimates can be calculated, known as the confidence limit analysis (Bargiela and Hainsworth 1989; Gabrys and Bargiela 1996).

In principle the above studies could be carried out on physical water distribution network. However, in practise the cost of purchasing and installation of the meters, and the time required for performing all the necessary experiments makes the exercise virtually impossible.

On the other hand, a large scale leakage detection studies are only possible in simulated environment. Such a study has been reported in (Gabrys 1997) and the simulation package described here has been used for generating data covering 24 hours of operations of a realistic water distribution network. Not only the data required for training a suitable fuzzy-neural pattern recognition system (Gabrys and Bargiela 1998) could be obtained in this way but extensive testing for frequently adverse conditions could be performed.

While the above briefly discussed methods and problems, making a wide use of the simulation package, have been reported in separate publications, the simulation package itself has not been described at greater length, anywhere so far.

## GENERAL DESCRIPTION OF THE SIMULATION PACKAGE

At the initial stages of the development of this simulation package the main goal was to facilitate on-line studies without recourse to physical water distribution system. It led to design of a *Simulation* module. In this module mathematical models of elements like pipes, valves, pumps etc. have been combined with exact information about network inflows and consumptions, network topology and physical dimensions of elements in order to calculate network's pressures and flows or in other words the exact state of the water network.

Since in the real world the absolutely accurate values of pressures and flows are unobtainable due to inherent uncertainty (e.g. inaccuracy of measurements, noise, prediction errors, malfunctions etc.) present in all complex systems a second module called *Telemetry* module has been added. As the name of the module suggests its main purpose is to simulate a physical telemetry system.

At present the package essentially consists of five self-contained modules performing specific tasks. These modules can be briefly described as follows:

- **Simulation** - it provides a facility to carry out on-line studies without recourse to a real life telemetry system; it calculates an exact state vector, given exact data. Using this module leakages or pipe blockages can be simulated by updating the topology information rather than opening hydrants or physically closing valves.
- **Telemetry** - using an exact state vector, supplied by the *Simulation* module, and information about the meter positioning this module first calculates the exact values of the measurements and then enables to introduce the measurement noise (according to a specification of the meters), simulate gross measurement errors and topological errors.
- **Estimation with CLA** - this module processes raw telemetered data and produces the state estimates with corresponding confidence limits. As would be the case in the real distribution network, no direct knowledge of any anomalous event simulated in the simulation module is available at this stage.
- **Classification** - the current state of the network, represented by the state estimates produced by *Estimation with CLA* module, are classified and assuming that the measurement errors have been identified and rejected at the estimation stage the topological errors like a leakage or wrong valve status should be detected and identified by this classification module.
- **Graphical network representation and user interface** - this module provides an easy access to all necessary information via the user friendly graphical environment. It also facilitates the control operations and change of input data and parameters.

A diagram representing the flow of information between different modules is shown at Figure 1. The simulations are driven from within the Graphical User Interface (GUI). The other four modules are grouped together and are executed in cycles. Each cycle involves the input data update, the execution of the four modules, and the output data update. The input data update takes into account all the changes (e.g. change of meter configuration, addition of a leakage, etc.) made by the user before the beginning of each new cycle. The output data update is concerned with the change of graphical display and suitable data fields representing the results of state estimation, confidence limit analysis and classification modules.

GUI is based on the two main windows depicted at Figure 2 and Figure 3. Figure 2 shows the main control window of the simulation package. Its basic function is to enable the simulation to be stopped and restarted, and to provide the user with control options via a set of pull-down menus and control buttons.

The second GUI window (Figure 3) is used for the graphical representation of a water distribution network and visualization of some of the simulation results. All the water network elements (i.e. nodes, pipes, reservoirs etc.) are modelled as graphical objects with a set of properties and actions associated with each of them. Information about current flows, pressures etc. is constantly available and can be displayed by using a mouse and choosing an

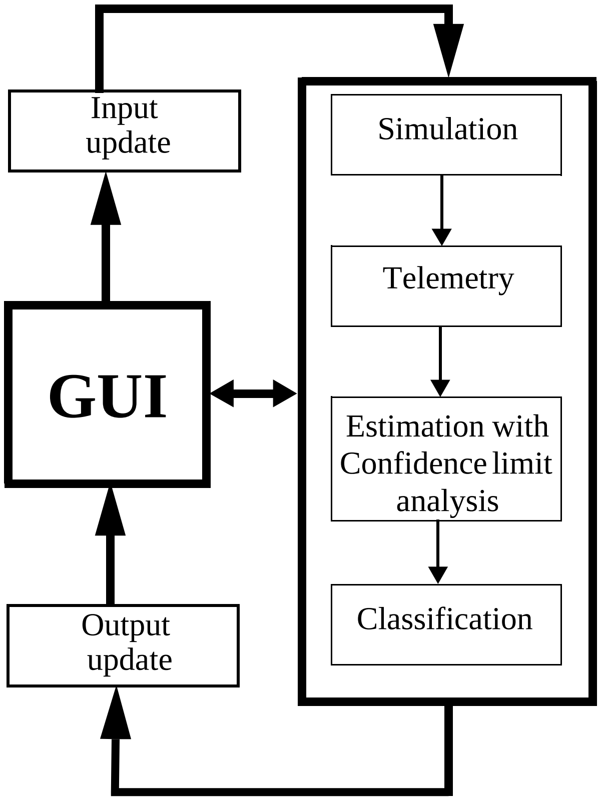


*Figure 1: Information flow in the simulation package.*

element of interest. The type of information obtained when choosing a pipe and a pipe with a valve is illustrated at Figure 4.

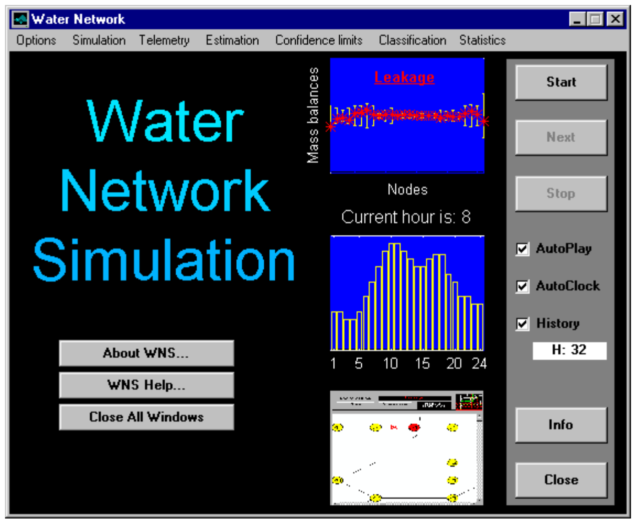


*Figure 2: The main GUI window for the water network simulation package.*

Apart from providing the access to the numerical data in the form shown at Figure 4 the GUI window at Figure 3 is also used for graphical visualization of the results of confidence limit analysis and identification of potentially leaking pipes. Showing confidence limits in a form of colour coded boxes or showing the

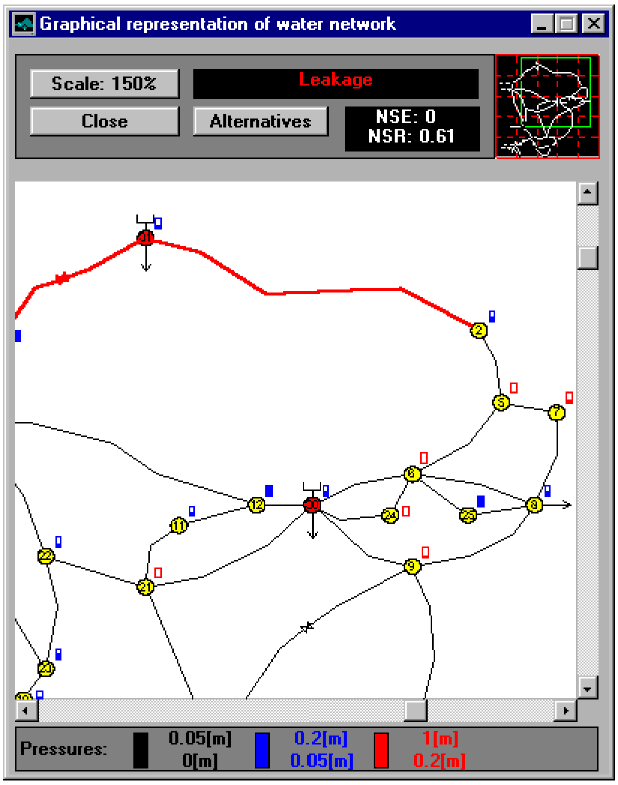


*Figure 3: A GUI window for graphical representation of water distribution network and visualization of simulation results.*

potential leakages in a form of changed thickness and colour of polylines representing the suspected pipes has proved to be more intuitive and informative for humans than a set of pressure and flow estimates.

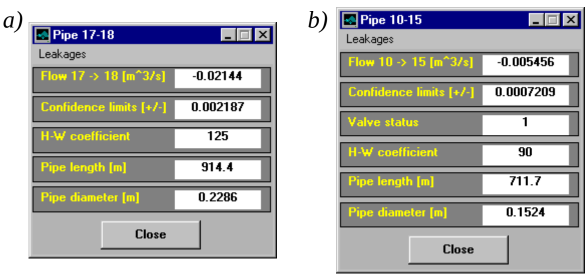


*Figure 4: Example of an on-line information for: a) a pipe; b) a pipe with a valve.*

The simulations can be executed in single cycles and the programme will wait for the user to initiate the next simulation cycle or the simulations can be run continuously. The continuous execution does not restrict the user in any way from changing the simulation parameters (e.g. introduction of a leakage etc.).

While the first type of execution is very useful when a thorough examination of the results of a single run is required the second type of execution is preferable when statistical data needs to be gathered or generation of a large amount of data for training or testing purposes is required.

Another important feature of this simulation package is its ability to switch between different characteristic operating conditions of the 24 hours of water distribution network operations. Both, manual (change from one period of time to another) and automatic (stepping through consecutive hours) options are supported. Using these options one can very quickly compare the performance of various algorithms for different operating conditions (e.g. 'night period' - low consumptions, smallest variations; 'peak load' - high consumptions, large variations) or gather/generate the data spanning the whole 24 hour period.

The following sections focus on a set of simulation problems that have been tackled using the package and demonstrate in this context some of the other important features of the software.

# SIMULATION BASED STUDIES

As it was mentioned in the introduction a number of studies carried for large, complex engineering systems is only feasible or economically viable in a simulated environment. The following examples illustrate how the simulation environment made the development and testing of some of the algorithms possible.

## Design and testing of state estimators

The problem of state estimation in water distribution networks is that of minimizing the discrepancies between the mathematical model of the system and a limited number of relatively accurate flow and/or pressure measurements supplemented by the less accurate predictions of consumptions at the network nodes.

The design of the most appropriate state estimation procedure involves careful considerations of the most likely errors that can occur in the system at hand. It is known that some state estimation procedures are more susceptible to certain types of errors than others. For instance, the least squares (LS) estimators are strongly affected by gross measurement errors while the least absolute value (LAV) estimators can produce unbiased estimates automatically rejecting the bad data. On the other hand, LS estimators are more robust than LAV estimators in a sense of convergence.

All meters configuration, their accuracy, the operation state of the network and occurrences of measurement errors have strong influence on the performance of state estimation procedures.

The ease with which the meters can be added and removed, gross errors and measurement noise introduced, the operating state switched from one to another has made this simulation package a very convenient tool both in design and testing phases of a development of state estimators.

The calculated pressures and flows are constantly updated and accessible via the GUI. The comparisons between different algorithms can be carried quickly and efficiently.

## Meter placement and confidence limits display

The location of meters about the water network strongly influences the accuracy of state estimates. By designing the meter placement in the telemetry system, it is possible to achieve a much higher level of monitoring accuracy.

An important factor to be considered when designing a meter configuration is the operating state of the network. Since the operating state of the system has a large effect on the way meter accuracy relates to state estimate accuracy, it is important that simulation includes variation of this state.

By selecting the appropriate control options from the GUI windows one can input a proposed meter configuration and/or change the operating state at any time of simulation execution.

The uncertainty in state estimates that would be produced by current meter configuration is constantly updated. The resultant confidence limits can be presented in a numerical form (see Figure 4) or can be displayed in a form of colour coded error blocks. The range of possible errors for each type of variable (i.e. pressure, flow) is divided into three smaller ranges. Each of these has its own colour. Every time the output update is performed rectangles representing the most recent confidence limits are drawn by the appropriate nodes or pipes in one of these three colours. The rectangles are filled in by certain amounts, representing the error bounds of these variables.

These colour coded error blocks are invaluable in deciding where to place meters or which meters to remove. A glance is all that is needed to see which parts of the network are weakly measured and thus require extra meters.

If the accuracy of the proposed meter placement is not acceptable in some way then it can be altered by either adding more meters, replacing some meters by more accurate ones or by moving some meters to different parts of the network. By experimenting with meter configuration in this way one can find a balance between accuracy and cost of metering.

The facilities for changing a measurement set make this simulation package flexible enough to cope with all metering scenarios and it means that satisfactory meter configuration can be found quickly and simply.

## Leakage detection and identification

An extensive performance studies for the 24 hours of water network operations, with a particular emphasis on detection and correct location of leakages, have been carried out using the simulation package described in this paper (Gabrys 1997).

First in order to obtain a representative set of data to train and then to test the neuro-fuzzy diagnostic system, the computer simulations have been used to generate data covering the 24 hour period for the water distribution network operation under various contingencies.

*Simulation of leakages*

In the simulation module, a leakage is modelled as an additional demand lying midway between the two end nodes of a pipe. This additional demand is not modelled as a pressure dependent variable and thus can be set to any desired value. The reservoir inflows and other network consumptions are adjusted to cover the additional demand resulting from a leakage. The pumping stations are assumed to produce a constant inflow and are not affected by leakages.

By systematically working through the network, ten levels of leakages were introduced, one at a time, in every single pipe for every hour of the 24 hour period. Such a comprehensive data set would be practically unobtainable from the physical system monitoring records and the simulations are the only way to generate it.

In the simulation package a combination of the fault detection based on state estimation residuals and the fault detection and identification based on state estimates is represented by the *Classification* module.

A number of features of the package is geared towards better visualization of the diagnostic results. When the diagnostic system is switched on, a combination of the text with graphical displays of different types is used in various places in order to create a fuller picture of a particular diagnosis.

The first example of such a combination is a graphical display of the residuals representing mass balances at network nodes (updated every cycle) against the confidence limits representing normal operating state (taken from pre-trained fault detection system). The graphical display is supplemented by the information text stating whether, according to the diagnostic results, it is a *normal operating state*, there is a *possible leakage* or there is a *leakage* present in the system (see the top display in Figure 2). The colour coding is also used for flagging emergency conditions. If any of the residual values falls outside the confidence limits for normal operating state, then the colour of the residuals is changed from its normal rendering to red.

The diagnostic results are also displayed in Figure 3 where the diagnosis is taken one step further and the possible locations of a leakage (if detected) are shown directly on the water network diagram by changing the thickness of lines and their colour (from normally black to red) thus flagging the suspected pipes. Further, the ranking of alternatives can be displayed (see Figure 5) in a form of a list of possibly leaking pipes sorted according to the membership values produced by the diagnosis system.

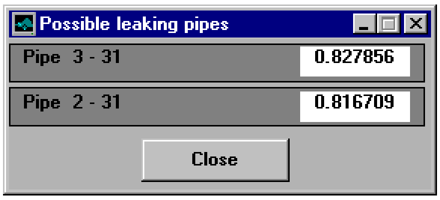


*Figure 5: An example of a list of alternatives produced by the diagnostic system.*

Due to the typical high levels of uncertainty, inadequate metering and changing of the operating conditions the instantaneous detection and location of leakages is frequently not possible or the diagnostic results can be confusing. It is frequently the case that for small leakages and/or during the periods of high consumption variations, the system can balance on the borderline of normal operating conditions and the possible fault occurrence is not being recognized by the diagnostic procedure. Another problem could be the fact that leakages in certain locations are more easily detected and located for some operating conditions than for others.

Rather than jump into action on the basis of confusing instantaneous diagnostic results the package offers an option of producing historical/statistical displays spanning longer periods of network operations. The inclusion of such a tool has been dictated by a simple observation that although the operating conditions can change dramatically over a period of few hours a leakage, if present, remains virtually the same and therefore can be more reliably detected over a longer period of time than on the basis of a single cycle.

The first of the statistical displays available is the split between the normal operation, possible leakage and leakage diagnosis generated over a period of time for which the data have been accumulated (Figure 6). The other three currently available statistical displays are generated/updated when a possible leakage or a leakage is diagnosed. They are used in an attempt to locate the leaking pipes and are calculated on the basis of analysis of: a) the top 5 alternatives in each simulation cycle (the top alternative is given the score of 1, the second - 0.8, the third - 0.6 etc.); b) the membership values generated from the neuro-fuzzy classification system; c) the occurrences as one of the possible alternatives (the alternatives with a membership values above a certain cut-off level are considered - an example of which is shown at Figure 7).

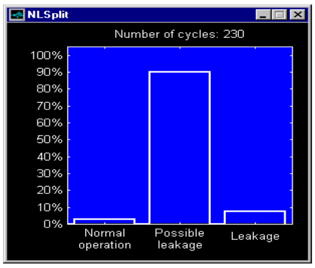


*Figure 6: The split between normal operation, possible leakage and leakage diagnosis for the 23 hour period of the network operations with a simulated leakage in a pipe between nodes 2 and 31.*

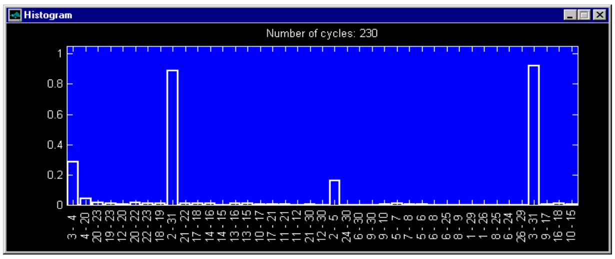


*Figure 7: The display of statistical data covering the 23 hour period of the network operation with a simulated leakage in a pipe between nodes 2 and 31.*

## SUMMARY

Computer simulations have become an essential part of problem solving in practically every engineering discipline as they provide engineers and researchers a tool to explore their worlds without having to run extensive physical, on site, experiments which tend to be expensive and time-consuming.

Modern water distribution networks with their complexity and large-scale are an example of such a system. The focus of this paper is on the simulation package for water distribution systems. A set of problems has been used to demonstrate an unquestionable value of the simulation package in analysis of water systems' behaviour and design of algorithms for their monitoring and control.

The package has been completely written in MATLAB environment (MATLAB). A combination of MATLAB's high-performance numeric computation and object based graphics resulted in fast executions within a user friendly environment with a relatively short prototype development time.

The modular structure of this package enables future substitutions, exclusions and more flexible way of changing (improving) some parts of the code without affecting the integrity of the software.

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